Final Report

DEMONSTRATION PROJECT RELATING TO STRESS ANALYSIS OF SWAGE-AUTOFRETTAGED AND RE-AUTOFRETTAGED GUN TUBES

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The principal investigator (APP), worked for a total of two weeks at Benet Research Laboratory, Watervliet, NY, using results from a dummy swage autofrettage FEA stress analysis in a non-linear stress analysis of the post heat treatment hydraulic re-autofrettage of a swaged tube. APP collaborated with Benet staff in: (a) Predicting permanent OD strains for a re-autofrettaged gun tube manufactured from HB7 steel. and (b) Devising material modeling procedures for use with ABAQUS/FEA aimed at incorporating Bauschinger effect. APP attended the 2007 ASME Pressure Vessels and Piping Conference in San Antonio, Texas, presenting two papers relating to autofrettage design. Subsequently the principal investigator (c) Developed the analyses relating to the demonstration project; (d) Collaborated with Mr. E. Troiano of Benet Labs and others in the preparation of a paper on material modeling for autofrettage analysis; (e) Provided a draft paper analyzing stresses due to swage autofrettage and hydraulic re-autofrettage of a gun tube; (f) Supplied a draft patent outline relating to hydraulic re-autofrettage of a swage-autofrettaged pressure vessel. The final patent application has now been submitted. This report contains descriptions and references relating to all significant project outcomes.

15. SUBJECT TERMS

Residual Stress, Autofrettage, Re-autofrettage, Swage, High Pressure, Non-Linear Numerical Solution,Finite Element Method

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ABSTRACT

The principal investigator, Anthony P. Parker (APP), worked for a total of two weeks at Benet Research Laboratory, Watervliet, NY, in conjunction with Mr. Edward Troiano and Mr. John Underwood using results from a dummy swage autofrettage FEA stress analysis of an A723 gun steel tube in a non-linear stress analysis of the post heat treatment hydraulic re-autofrettage of a swaged tube.

APP collaborated with Benet staff in:

(a) Predicting permanent OD strains for a re-autofrettaged gun tube manufactured from HB7 steel.

(b) Devising material modeling procedures for use with ABAQUS/FEA aimed at incorporating Bauschinger effect.

APP attended the 2007 ASME Pressure Vessels and Piping Conference in San Antonio, Texas, presenting two papers relating to autofrettage design. Subsequently the principal investigator:

(c) Developed the analyses relating to the demonstration project.

(d) Collaborated with Mr. E. Troiano of Benet Labs and others in the preparation of a paper on material modeling for autofrettage analysis.

(e) Provided a draft paper analyzing stresses due to swage autofrettage and hydraulic re-autofrettage of a gun tube.

(f) Supplied a draft patent outline relating to hydraulic re-autofrettage of a swage-autofrettaged pressure vessel. The final patent application has now been submitted.

This report contains descriptions and references relating to all significant project outcomes.

OVERVIEW OF PROJECT OUTCOMES

1. The principal investigator, Professor Anthony P. Parker (APP), worked for a total of two weeks at Benet Research Laboratory, Watervliet, NY, in conjunction with Mr. Edward Troiano and Mr. John Underwood.
2. During this period APP used results from a dummy swage autofrettage ANSYS/FEA stress analysis of an A723 gun steel tube as the basis for a non-linear stress analysis of the post heat treatment hydraulic re-autofrettage of a swaged tube.
3. In addition APP collaborated with Troiano and Underwood in:
   a. Predicting permanent OD strains for a re-autofrettage gun tube manufactured from HB7 steel. This lead to the conclusion that experimentally measured improvement in Safe Maximum Pressure (SMP) in A723 tubes arises from the effects of retained strain hardening following the initial autofrettage process. This, in turn, effectively enhances yield strength for subsequent processes.
   b. Devising material modeling procedures for use with ABAQUS/FEA aimed at incorporating Bauschinger effect. Two possible procedures were identified, namely an Elastic Modulus and Poissons Ratio Adjustment procedure and a separate procedure based upon the introduction of a ‘Single effective material’.
4. Following his attachment to Benet Labs, APP attended the ASME Pressure Vessels and Piping Conference in San Antonio, Texas. He presented two papers relating to autofrettage design [1, 2]. APP was also co-author on two further papers [3, 4].

5. APP subsequently worked for a total of a further four weeks developing the analyses relating to this demonstration project.
6. APP collaborated with Mr. E. Troiano of Benet Labs and others in the preparation of a paper on Material Modeling for Autofrettage Stress Analysis [5] to be delivered at the 2008 ASME Pressure Vessels & Piping Conference, Chicago, July 2008.
7. APP provided a draft paper analyzing stresses due to swage autofrettage and hydraulic re-autofrettage of a gun tube [6]
8. APP supplied a draft patent outline, based upon [6], relating to hydraulic re-autofrettage of a swage-autofrettaged pressure vessel. This patent had previously received protective registration. On 23 May 2008 the final patent application was submitted [7]. All rights have been assigned to the US Army.

SIGNIFICANT RESULTS

Three of the above outcomes present significant new results. These are fully described in references [5], [6] and [7].

a. The 'Single Effective Material' (Ref [5]).

Analytical and numerical stress analysis of the autofrettage process has made great strides in the last few years. The major challenge is no longer the stress analysis process but the incorporation of 'real' material behavior, including Bauschinger effect. This means that material properties may vary at every radial location within the tube.

In this paper it is demonstrated that Finite Element Analysis (FEA) may be accomplished using a 'user programmable feature' within a non-linear FEA or, more simply using an elastic modulus and Poisson's ratio adjustment procedure within a linear-elastic FEA. The results of these two methods are shown to be in agreement with each other and with an independent numerical analysis.
It is further demonstrated that numerical solutions may be obtained using a single 'fictitious' material. This is called a 'single equivalent material' (SEMAT). Whilst this requires a very small number of iterations for accurate convergence, it dramatically reduces the material-modeling challenges.

Figure 1, taken from [5], illustrates the close agreement between a conventional stress analysis requiring complex representation of varying material behavior and the proposed SEMAT procedure.

Furthermore, SEMAT may be implemented into an analytical procedure thereby permitting highly accurate modeling of a real material whose unloading behavior varies with radius. Comparisons indicate that this is a robust, accurate procedure.

The above procedure is distinctly different from hydraulic autofrettage followed by heat soak and further hydraulic re-autofrettage..

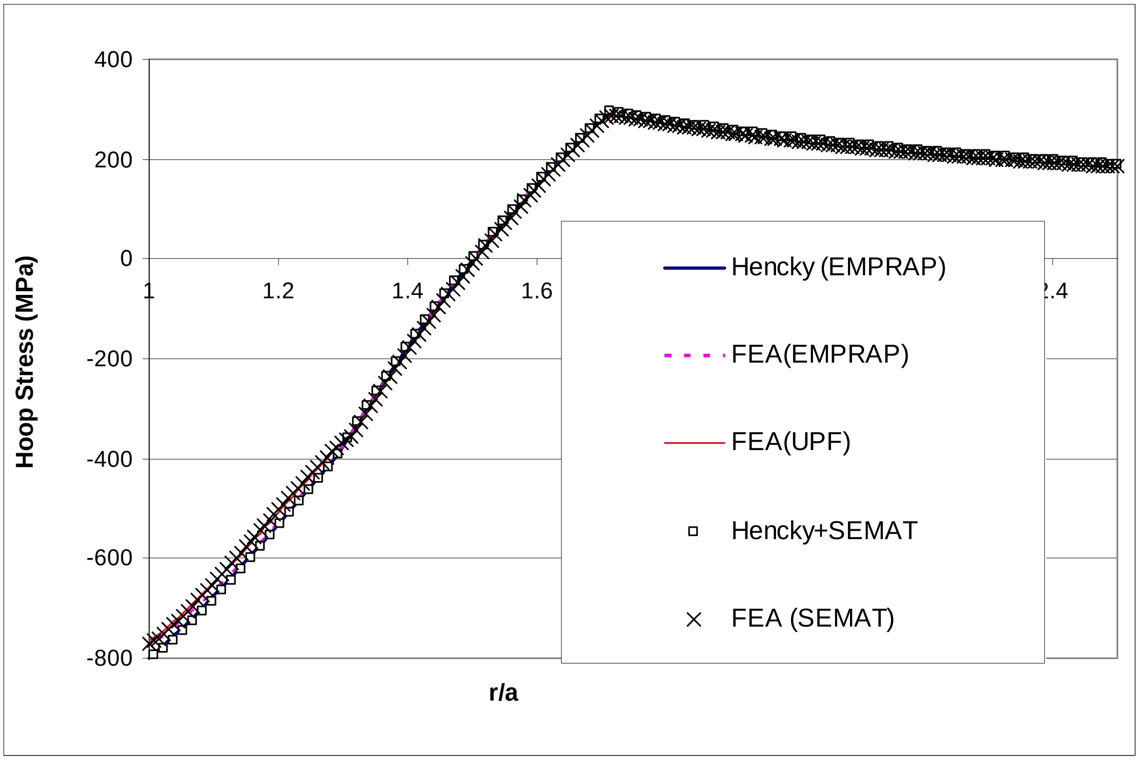

Figure 1: Hoop Residual Stress in an Autofrettaged Thick Cylinder Calculated Using the SEMAT procedure and Alternative Numerical Analysis Methods (from ref. [5]).

b. Numerical Analysis of a Swaged and Re-autofrettaged Tube (Ref [6]).

An earlier report presented a non-linear analysis of hydraulic re-autofrettage following initial swage autofrettage and heat soak. The initial swage autofrettage residual stress field in that case was based upon results from a neutron-diffraction experiment. The apparent benefits in that case derived mainly from the adjustment of stress fields within the wall of the tube, close to the original elastic-plastic interface created during the swage process. Bauschinger effect mitigation was a second order effect.

Here, the initial (post-swage) residual stress field was determined numerically using an enhanced Finite Element program. Once again, it is predicted that re-autofrettage can produce improvements in safe maximum pressure as defined by additional permanent strain. At higher re-autofrettage pressures OD residual hoop stresses increase significantly. Figure 2 (taken from [6]) illustrates the stress and pressure variations.

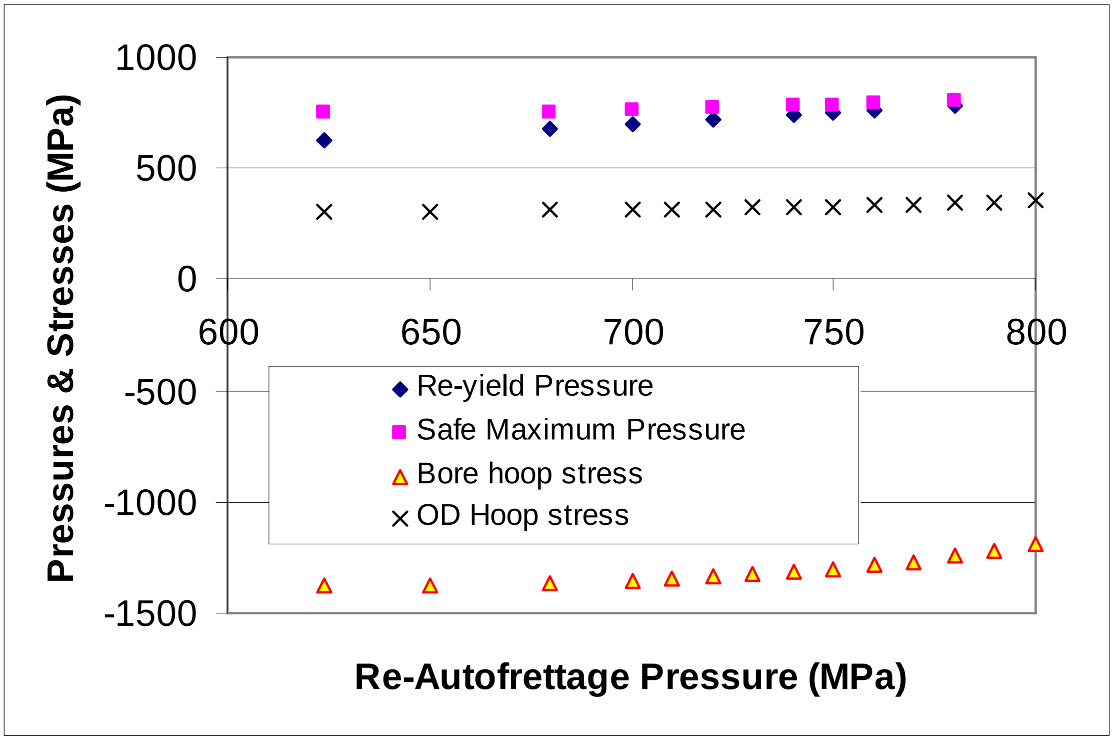

Figure 2: Safe Maximum pressure, Re-yield pressure, Compressive Bore Hoop Stress and OD Hoop Stress as a Function of Re-autofrettage Pressure.

In summary:

1. Initial re-yielding occurs at original (swage) elastic-plastic interface and extends radially inwards and outwards.. The reason for the interior re-yielding is the significantly higher residual stress gradient associated with swage autofrettage.
2. The residual hoop stress within the re-yielded region has the gradient associated with hydraulic autofrettage.
3. Over the entire range re-yield pressure = re-autofrettage pressure.
4. In the case considered there is a modest monotonic reduction in residual compressive bore hoop stress. This is explained by by the need to maintain force equilibrium after re-yielding.
5. Safe maximum pressure (SMP) rises monotonically as re-autofrettage pressure is increased.
6. There is a monotonic increase in residual tensile OD hoop stress. Such hoop stresses, if magnified by stress concentrators, could produce early-life OD failures.
7. Although not reported in [6], there is evidence that the pressures achieved during experimental SMP testing of re-autofrettaged tubes actually exceed those predicted via a numerical analysis that assumes little or no retained strain hardening. *The explanation of these significantly higher experimental pressures is likely associated with the retention, and increase, of strain hardening during re-autofrettage and should be a priority for future work*.

c. Patent (Ref [7]).

The patent application is based upon ref [8], a report prepared on an earlier contract. It describes the following sequence:

1. Initial swage autofrettage;
2. One or more (heat soak + hydraulic autofrettage) sequences; and
3. An optional final heat soak.

the above sequence is claimed to enhance safe maximum pressure and/or fatigue lifetime.

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[3] Underwood, J. H., deSwardt, R. R., Venter, A. M., Troiano, E., Hyland, E. J. and Parker, A. P., 2007, "Hill Stress Calculations for Autofrettaged Tubes Compared With Neutron Diffraction Residual Stresses and Measured Yield Pressure and Fatigue Life, Paper PVP2007-26617, ASME 2007 Pressure Vessels and Piping Conference, San Antonio, TX.

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[6] Parker, A. P, Troiano, E., and Underwood, J. H., "Numerical analysis of a Swaged and Re-autofrettaged Tube", Draft Paper submitted to Benet Labs, May 2008.

[7] Parker, A. P., Troiano, E., Underwood J. H., "Multiple Autofrettage", US Army Invention Disclosure 2006-025 – July 2006. Subsequent Patent Application # 60/939,671 filed on 23 May 2007, Final Applicatio submitted 22 May 2008.

[8] Parker, A. P., Underwood, J. H. and Troiano, E., 2006, "Hydraulic Re-autofrettage of a Swage Autofrettaged Tube", Unpublished paper, not cleared for release, Benét Laboratories, Watervliet Arsenal, NY 12189, USA.

Professor A P Parker **23** ***May 2008***

Annex

(a) Unused federal funds remaining at end of period covered by this report : $0.00
(b) No property was acquired with contract funds during the period of this report.